Integrating of Arterial Signal and Freeway Off-ramp Controls for Commuting Corridors

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Outline

1. Research Background & Literature Review
2. Primary Tasks & System Framework
3. Model Formulations
4. Conclusions and Future Research Directions
Congestion at Off-ramp Interchanged Area

Freeway

Arterial

Bottleneck

Off-
Field Observations
(National Highway No. 1, Chupei, Taiwan)

(A) Speed obtained by upstream detectors
(B) Speed obtained by downstream detectors
Integrated Off-Ramp Controls

Freeway

Intersection Signal Control

Arterial

Off-Ramp Interchange

Signal Coordination Control

Off-Ramp Queue Spillover Prevention

Integrated Off-ramp Traffic Control
Literature Reviews

- Pre-timed Signal Optimization Models
- Real-time Signal Control Models
- Integrated Control Models

Existing Studies
### Literature Reviews

**Pre-timed Signal Optimization Models**

**Signal optimization at isolated intersections**

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Pre-timed Signal Optimization Models

Signal optimization at arterial level

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<th>Maximizing Progression Efficiency</th>
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<td><strong>TRANSYT</strong> (Robertson, 1969); <strong>TRANSYT 7-F</strong> (Wallace et al., 1988); <strong>Simulation-based</strong> (Yun and Park, 2006, Stevanovic et al., 2007); <strong>CTM-based</strong> (Lo, 1999; Lo et al., 2001; and Lo and Chow 2004); <strong>Others</strong> (Aboudolas et al., 2010; Zhang and Yin 2010, Li, 2012, Liu and Chang, 2011)</td>
<td>Morgan and Litter (1964), Litter (1966), Little et al., (1981), Gartner et al. (1991), Chaudhary et al. (2002), Tian and Urbanik (2007), Li (2014)</td>
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## Literature Reviews

### Real-time Signal Control Models

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<th>Adaptive Signal Control</th>
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<td><strong>System Introduction</strong> (Boillot et al. 1992; ITE, 1997)</td>
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<td><strong>Max green time selection</strong> (Lin, 1985; Courage et al., 1989; Orcutt , 1993; Kell and Fullerton, 1998; Courage , 2003; Zhang and Wang, 2011)</td>
<td><strong>OPAC</strong> (Gartner et al., 1979; Gartner, 1983; Gartner et al., 1995; Gartner et al., 2001)</td>
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## Literature Reviews

### Integrated Control Models

#### Integrated Corridor Control

Integration of multiple strategies such as:
- traffic diversion
- on-ramp metering
- speed limit control
- signal timing controls

(Cremer and Schoof, 1989; Zhang and Hobeika, 1997; Wu and Chang, 1999; Chang et al., 1993; Papageorgiou, 1995; Berg et al., 2001; Li, 2010; Haddad et al., 2013)

#### Off-ramp Control

- Eliminating the lane changing maneuvers (Daganzo et al., 2002; Rudjanakanoknad, 2012; Di et al., 2013)

- Detouring the flows to other non-congested areas (Gunther et al., 2012; Spiliopoulou et al., 2013, 2014)

- Optimizing signal timing at neighboring intersections (Messer, 1998; Tian et al., 2002; Li et al., 2009; Lim et al., 2011; Yang et al., 2014)
Findings of Literature

- Signal controls at arterial level (pre-timed & real-time): may fall short of providing efficiency control at the off-ramp interchanged area;

- Integrated corridor control: may not be able to find the optimal solution for system control variables;

- Off-ramp control with restricting lane changing or detouring flows: may not be applicable in practice;

- Off-ramp control with signal optimization at neighboring intersections: more practical but many critical issues remain to be solved!
1. Research Background & Literature Review
2. Primary Tasks & System Framework
3. Model Formulations
3. Conclusions and Future Research Directions
Critical Research Issues

I – How to facilitate traffic flows to reach their destinations?

II – How to analyze the demand pattern at the interchange?

III – How to optimize the signal plans to prevent the off-ramp queue spillover?

IV – How to deal with the uncertainty of vehicles’ arrivals using real-time control functions?

V – How to deal with the uncertainty of vehicles’ arrivals using real-time control functions?
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O-D Estimation Model

Identify traffic flows’ origins and destinations

Identify Critical Path
Critical Research Issues

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Model Development

- Traffic Detectors
  - Historical Traffic Data
    - OD Estimation Model
    - OD flow pattern
    - Critical Traffic Paths
  - Signal Optimization Model
    - Multi-path Progression Model
    - Pre-timed Signal Plan
  - Real-time signal Control
In the literature, the main purpose of most O-D estimation models is providing essential information for traffic assignment or network simulation.

However, designing of signal plan at the off-ramp interchanged area have also raised the need of using O-D estimation for identifying critical traffic paths.
Origin-Destination Estimation

Based on the dynamic O-D estimation technique, this study proposed three models with different measurement inputs:

- Model I: only the link count data are available;
- Model II: turning volumes at each intersection are available;
- Model III: both intersection turning flows and real-time queue information are obtainable for model estimation.
Only the **link count** data are available
O-D Estimation: Model I

Flow conservations and diversions

\[ y_j(k) = \sum_{i=1}^{2N+2} \left[ q_i(k - \tau_{ij}^{k+}) \rho_{ji}^{+} y_j(k - \tau_{ij}^{k-}) b_j(k - \tau_{ij}^{k-}) + q_i(k - \tau_{ij}^{k-}) \rho_{ji}^{-} y_j(k - \tau_{ij}^{k+}) b_j(k - \tau_{ij}^{k+}) \right] \]

\[ \rho_{ji}^{+}(k) + \rho_{ji}^{-}(k) = 1 \]

\[ u_i^{in}(k) = \sum_{i=1}^{2l+1} \sum_{j=2l+2}^{2N+2} \left[ q_i(k - \tau_{ii}^{k+}) \theta_{ii}^{+} y_i(k - \tau_{ii}^{k-}) b_i(k - \tau_{ii}^{k-}) + q_i(k - \tau_{ii}^{k-}) \theta_{ii}^{-} y_i(k - \tau_{ii}^{k+}) b_i(k - \tau_{ii}^{k+}) \right] \]

\[ u_i^{out}(k) = \sum_{i=2l}^{2N+2} \sum_{j=0}^{2l-1} \left[ q_i(k - \tau_{ii}^{k-}) \theta_{ii}^{-} y_i(k - \tau_{ii}^{k+}) b_i(k - \tau_{ii}^{k+}) + q_i(k - \tau_{ii}^{k+}) \theta_{ii}^{+} y_i(k - \tau_{ii}^{k-}) b_i(k - \tau_{ii}^{k-}) \right] \]

\[ \sum_{m=0}^{M} \theta_{ij}^m(k) \theta_{jl}^+(k) + \theta_{ij}^m(k) \theta_{jl}^-(k) = 1 \]
Estimation Algorithm

The dynamic O-D variables are assumed to follow the random walk process between successive time intervals:

\[ b_{ij}(k+1) = b_{ij}(k) + w^b_{ij}(k), \quad 1 \leq i, j \leq 2N + 2 \]

\[ \rho^-_{ij}(k+1) = \rho^-_{ij}(k) + w^\rho_{ij}(k), \quad 1 \leq i, j \leq 2N + 2 \]

\[ \theta^-_{il}(k+1) = \theta^-_{il}(k) + w^\theta_{il}(k), \quad 1 \leq i \leq 2N + 2; 1 \leq l \leq N \]
Compute the linearized transformation matrix $H(k)$

Update the estimation with extended Kalman filter

- $X^-(k) = X(k-1)$; $P^-(k) = P(k-1) + Q$
- $K(k) = P^-(k)H^T(k)(H(k)P^-(k)H^T(k) + R)^{-1}$
- $X(k) = X^-(k) + K(k)[z(k) - h(X^-(k))]$
- $P(k) = [I - K(k)H(k)]P^-(k)$
Turning volumes at each intersection are available
O-D Estimation: Model II

Flow conservations and diversions

For approach 2 and 4:

\[ \eta_{2l}^L (k) = \sum_{i=2l+2}^{2N+2} \sum_{m=t_i^L}^{r_i^L+1} q_i (k-m) \theta_{i,j}^m (k-m) b_{i,2l+1} (k-m) \]

\[ \eta_{2l}^T (k) = \sum_{i=2l+2}^{2N+2} \sum_{m=t_i^T}^{2l-1} q_i (k-m) \theta_{i,j}^m (k-m) b_{j} (k-m) \]

\[ \eta_{2l}^R (k) = \sum_{i=2l+2}^{2N+2} \sum_{m=t_i^R}^{r_i^R+1} q_i (k-m) \theta_{i,j}^m (k-m) b_{1,2l} (k-m) \]

\[ \eta_{4l}^L (k) = \sum_{i=1}^{2l-1} \sum_{m=t_i^L}^{r_i^L+1} q_i (k-m) \theta_{i,j}^m (k-m) b_{1,2l} (k-m) \]

\[ \eta_{4l}^T (k) = \sum_{i=1}^{2l-1} \sum_{m=t_i^T}^{2N+2} \sum_{j=2l+2}^{r_j^T+1} q_i (k-m) \theta_{i,j}^m (k-m) b_{j} (k-m) \]

\[ \eta_{4l}^R (k) = \sum_{i=1}^{2l-1} \sum_{m=t_i^R}^{r_i^R+1} q_i (k-m) \theta_{i,j}^m (k-m) b_{1,2l+1} (k-m) \]
O-D Estimation: Model III

Both intersection **turning flows** and **real-time queue information** are obtainable for model estimation.

- **Camera Sensors**
- **Radar Sensors**
Queue Length Estimation

\[
\begin{align*}
\delta^T_{l,l-1}(k) &= \sigma^T_{l,l-1}(k) + \varphi_T (\eta^R_{1,l} \xi^T_{1,1} + \eta^T_{1,l} \xi^T_{1,1} + \eta^L_{1,l} \xi^T_{1,1}) \\
\delta^L_{l,l-1}(k) &= \sigma^L_{l,l-1}(k) + \varphi_L (\eta^R_{1,l} \xi^L_{1,1} + \eta^T_{1,l} \xi^L_{1,1} + \eta^L_{1,l} \xi^L_{1,1}) \\
\delta^R_{l,l-1}(k) &= \sigma^R_{l,l-1}(k) + \varphi_R (\eta^R_{1,l} \xi^R_{1,1} + \eta^T_{1,l} \xi^R_{1,1} + \eta^L_{1,l} \xi^R_{1,1})
\end{align*}
\]

\(\delta^i_{l,l-1}(k)\) is the queue length at the end of red phase on lane group \(i\);

\(\sigma^i_{l,l-1}(k)\) is the queue length at the start of red phase on lane group \(i\);

\(\varphi_i\) is the lane use factor for lane group \(i\);

\(\xi^j_{i,l}\) is a ratio which represents the portion of flow \(\eta^m_{i,l}\) that will join downstream flow \(\eta^i_{2,l-1}\);

\(r^j_{i,l}\) is a ratio which represents the portion of uncoordinated flows;
Queue Length Estimation

For outbound direction:

\[
\delta_{i,j-1}^p(k) = \sigma_{i,j-1}^p(k) + \varphi_p \left[ \sum_{j=1}^{2l-1} \sum_{m=t_2,i,j}^{2l,j+1} q_{2l}(k-m) \theta_{2l,i,j}^m(k-m)b_{2l,i,j}(k-m) \right] \xi_{2l,i}^p r_{2l,i}^p \\
+ \left( \sum_{l=2l+1}^{2N+2} \sum_{m=t_2,i,j}^{2l,j+1} q_{2l}(k-m) \theta_{2l+1,i,j}^m(k-m)b_{2l+1,i,j}(k-m) \right) \xi_{2l,i}^p r_{2l,i}^p; \quad \forall p \in \{L, T, R\}
\]

For inbound direction:

\[
\delta_{i,j+1}^p(k) = \sigma_{i,j+1}^p(k) + \varphi_T \left[ \sum_{j=1}^{2l-1} \sum_{m=t_2,i,j}^{2l,j+1} q_{2l}(k-m) \theta_{2l,i,j}^m(k-m)b_{2l,i,j}(k-m) \right] \xi_{2l,i}^p r_{2l,i}^p \\
+ \left( \sum_{l=1}^{2l+1} \sum_{m=t_2,i,j}^{2l,j+1} q_{2l}(k-m) \theta_{2l+1,i,j}^m(k-m)b_{2l+1,i,j}(k-m) \right) \xi_{2l,i}^p r_{2l,i}^p; \quad \forall p \in \{L, T, R\}
\]
Model Evaluation

Arterial Topology of the Study Site

<table>
<thead>
<tr>
<th>Models</th>
<th>Model I</th>
<th>Model II</th>
<th>Model III</th>
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<tbody>
<tr>
<td></td>
<td>MAE</td>
<td>MAPE</td>
<td>RMSE</td>
</tr>
<tr>
<td>Link flows</td>
<td>4.54</td>
<td>18.56%</td>
<td>5.48</td>
</tr>
<tr>
<td></td>
<td>3.99</td>
<td>15.92%</td>
<td>4.99</td>
</tr>
<tr>
<td>Turning flows</td>
<td>4.02</td>
<td>42.39%</td>
<td>5.54</td>
</tr>
<tr>
<td></td>
<td>2.70</td>
<td>17.46%</td>
<td>3.92</td>
</tr>
<tr>
<td>OD flows</td>
<td>1.885</td>
<td>42.02%</td>
<td>3.075</td>
</tr>
<tr>
<td></td>
<td>1.251</td>
<td>28.11%</td>
<td>1.979</td>
</tr>
</tbody>
</table>
# Model Evaluation

![Network Diagram](image)

<table>
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<th>Ground Truth</th>
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<th>Model II</th>
<th>Model III</th>
</tr>
</thead>
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<tr>
<td><strong>OD Pair</strong></td>
<td>OD Pair</td>
<td>Total Flows</td>
<td>OD Pair</td>
</tr>
<tr>
<td>9→12</td>
<td>1390</td>
<td><strong>9→12</strong></td>
<td>1658</td>
</tr>
<tr>
<td>6→12</td>
<td>765</td>
<td><strong>6→12</strong></td>
<td>985</td>
</tr>
<tr>
<td>9→1</td>
<td>756</td>
<td>9→4</td>
<td>649</td>
</tr>
<tr>
<td>6→4</td>
<td>729</td>
<td>4→7</td>
<td>497</td>
</tr>
<tr>
<td>12→7</td>
<td>553</td>
<td>4→8</td>
<td>465</td>
</tr>
<tr>
<td>12→1</td>
<td>472</td>
<td><strong>9→1</strong></td>
<td>427</td>
</tr>
</tbody>
</table>
Pre-timed Signal Design

- Traffic Detectors
- OD Estimation Model
- OD flow pattern
- Critical Traffic Paths
- Historical Traffic Data
- Signal Optimization Model
- Multi-path Progression Model
- Pre-timed Signal Plan
- Real-time signal Control
Pre-timed Signal Design

Signal Optimization Model

Objective: maximizing intersection capacity
Control Variables: common cycle length, green split

Multi-path Progression Model

Objective: maximizing progression efficiency
Control Variables: offsets; phase sequences
Signal Timing Optimization

Objective function: Maximization of Intersection capacity

Apply a multiplier $\mu$ to the demand pattern

Given demand pattern

Apply a multiplier $\mu$ to the demand pattern

The demand reach the capacity of the intersection

Give arrival pattern, capacity is usefully measured by how large a multiplier $\mu$ can be applied to the demand.

Then, the capacity of the intersection could be indicated by the multiplier $\mu$.

REF: S.C. Wong et al. (2003)
Signal Timing Optimization

\[ M1: \text{Maximize } \sum_i \mu_i \rightarrow \text{Maximization of intersection capacities} \]

\[ s.t. \]

\[ \mu_i \alpha_{k,i} q_{k,i} \leq s_{k,i} \sum_m \beta_{k,m,i} \Phi_{m,i} - \delta \times \xi \quad \forall i, k \rightarrow \text{Flow } \leq \text{Link Capacity} \]

\[ \sum_m \Phi_{m,i} = 1 \quad \forall i \rightarrow \text{Sum of green } = \text{cycle length} \]

\[ (1 - \sum_m \beta_{o,m,i} \Phi_{m,i} + \delta \times \xi) \cdot q_{o,i} \cdot s_{o,i} \leq \tau_{o,i}^{\max} (s_{o,i} - q_{o,i}) \xi \rightarrow \text{Off-ramp queue constraint: Queue } < \text{Link Length} \]

\[ \frac{1}{C_{\max}} \leq \xi \leq \frac{1}{C_{\min}} \rightarrow \text{Min & Max cycle length} \]

\[ \xi \times g_{\min} \leq \Phi_{m,i} \leq \xi \times g_{\max} \quad \forall m, i \rightarrow \text{Min & Max green time} \]
Pre-timed Signal Design

Signal Optimization Model

Objective:
- maximizing intersection capacity
Control Variables:
- common cycle length, green split

Multi-path Progression Model

Objective:
- maximizing progression efficiency
Control Variables:
- offsets; phase sequences
Within the green band, vehicles can pass the intersections without any stops.
What is Multi-Path Progression?
Critical Issues in Multi-Path Progression

1. How to formulate the optimization model to accommodate multiple traffic paths?

2. How to concurrently optimize the phase sequences?

3. How to effectively eliminate some paths so as to produce the maximal progression benefit?
Model I

• Control Objective:

\[
\text{Max } \sum_i (\varphi_i b_i + \bar{\varphi}_i \bar{b}_i)
\]

• Interference Constraints:

\[
0 \leq w_{i,k} + b_i \leq g_{i,k}
\]

\[
0 \leq \bar{w}_{i,k} + \bar{b}_i \leq \bar{g}_{i,k}
\]

- \(b_i\): Bandwidth of an inbound path
- \(b\downarrow i\): Bandwidth of an outbound path
- \(\varphi_i\), \(\varphi\downarrow i\): Weighting factors
- \(g\downarrow i,k\): Green time for an inbound path \(i\) at intersection \(k\)
- \(g\downarrow i,k\): Green time for an outbound path \(i\) at intersection \(k\)

- \(w\downarrow i,k\): Part of green time that is before the band for an inbound path \(i\) at intersection \(k\)
- \(w\downarrow i,k\): Part of green time that is after the band for an outbound path \(i\) at intersection \(k\)
Model I

- P1 Constraints:

For inbound directions:

where, $r_{↓\ldots\downarrow}k$, $k$ is the total red time path $\ldots\downarrow k$ experienced before the start of green at intersection $\ldots\downarrow k$.

For outbound directions:

where, $r_{↓\ldots\downarrow}k$, $k$ is the total red time path $\ldots\downarrow k$ experienced after the green time at intersection $\ldots\downarrow k$.

$\theta_{↓\ldots\downarrow}k \cdot w_{↓\ldots\downarrow}k = 0$

$\theta_{\downarrow k+2} - \theta_{\downarrow k+1}$

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Model II

• Model 2: To optimize the phase sequence in the multi-path progression model.

• To facilitate the phase sequence optimization, a set of binary variables are defined as follows:

\[ x_{l,m,k} = \begin{cases} 
1, & \text{if phase } l \text{ is before phase } m \text{ within the same cycle of intersection } k; \\
0, & \text{o.w.} 
\end{cases} \]
Model II

- To ensure the feasibility of the generated phase sequence, a set of constraints are defined as follows:

\[
x_{l,l,k} = 0 \quad \forall l; \forall k
\]

A phase is never before itself.

\[
x_{l,m,k} + x_{m,l,k} = 1 \quad \forall l \neq m; \forall k
\]

Either phase \( l \) is before phase \( m \), or phase \( m \) is before phase \( l \).

\[
x_{l,n,k} \geq x_{l,m,k} + x_{m,n,k} - 1 \quad \forall l \neq m \neq n; \forall k
\]

If phase \( l \) is before phase \( m \) and phase \( m \) is before phase \( n \), phase \( l \) must be before phase \( n \).

\[
x_{l,n,k} + x_{n,m,k} = 1 \quad l \neq m \neq n
\]

(optional)Phase \( l \) and \( m \) are in a sequential order

\[
x_{l,m,k} = 1 \quad l \neq m
\]

(optional)Phase \( l \) must be before phase \( m \)
Model II

• The interference constraints must be re-written as follows:

A set of binary parameters are defined to represent the phasing design:

\[
\beta_{i,l,k} = \begin{cases} 
1, & \text{if path } i \text{ obtains green in phase } l \text{ at intersection } k; \\
0, & \text{o.w.}
\end{cases}
\]

\[
0 \leq w_{i,k} + b_i \leq \sum_l \beta_{i,l,k} \phi_{l,k} \quad \forall i \in \Omega; \forall k \in \sigma_i
\]

\[
0 \leq \bar{w}_{i,k} + \bar{b}_i \leq \sum_l \beta_{i,l,k} \phi_{l,k} \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i
\]
Model II

Similarly, the progression constraints are given as follows:

For inbound directions:
\[
\theta_k + \bar{r}_{i,k} + w_{i,k} + t_{i,k,k+1} + n_{i,k} = \theta_{k+1} + \bar{r}_{i,k+1} + w_{i,k+1} + n_{i,k+1}
\]

For outbound directions:
\[
\theta_{k+1} - \theta_k + \bar{r}_{i,k} + w_{i,k} + t_{i,k,k+1} + n_{i,k} = \bar{r}_{i,k+1} + w_{i,k+1} + n_{i,k+1}
\]

- \( w\downarrow i,k \) : portion of green time that is before the band for an inbound path \( i \) at intersection \( k \)
- \( w\downarrow i,k \) : portion of green time that is after the band for an inbound path \( i \) at intersection \( k \)
- \( t\downarrow k \) : travel time between intersection \( k \) and \( k+1 \)
- \( t\downarrow k+1 \) : travel time between intersection \( k+1 \) and \( k \)

\[
r_{i,k} \leq \sum \beta_{i,m,k} x_{l,m,k} \cdot \phi_{l,k} + M (1 - \beta_{i,m,k}) \quad \forall i \in \Omega + \bar{\Omega} ; \forall k \in \sigma_i ; \forall m
\]

\[
\bar{r}_{i,k} \leq \sum \beta_{i,m,k} x_{m,l,k} \cdot \phi_{l,k} + M (1 - \beta_{i,m,k}) \quad \forall i \in \Omega + \bar{\Omega} ; \forall k \in \sigma_i ; \forall m
\]

\[
r_{i,k} + \bar{r}_{i,k} + \sum \beta_{i,l,k} \cdot \phi_{k,n} = 1 \quad \forall i \in \Omega + \bar{\Omega} ; \forall k \in \sigma_i
\]
Model III

- Progression competition between different critical paths

- In practice, the identified critical paths may compete for the progression band.

- Thus, it might be infeasible or ineffective to find a synchronization plan which can offer reasonable bandwidths for all the critical paths.

- Hence, it is essential to eliminate some infeasible paths when designing signal progression.
Model III

To deal with the progression conflicts between critical paths, another set of constraints are introduced as follows to the model:

\[
y_i = \begin{cases} 
1 & \text{if path } i \text{ obtains signal progression with non-zero green band} \\
0 & \text{o.w.} 
\end{cases}
\]

\[
b_i \leq y_i, \quad \bar{b}_i \leq y_i
\]

For inbound directions:

\[
\theta_k + r_{i,k} + w_{i,k} + t_{i,k} + n_{i,k} \geq \theta_{k+1} + r_{i+1,k} + w_{i+1,k} + t_{i+1,k} + n_{i+1,k} - M (1 - y_i)
\]

It is similar for outbound directions.
Model Summary

Max $\sum_i (\varphi_i b_i) + \sum_i (\varphi_i \tilde{b}_i)$

Subject to

$0 \leq w_{i,k} + b_i \leq g_{i,k} \quad \forall i \in \Omega; \forall k \in \sigma_i$

$0 \leq \bar{w}_{i,k} + \bar{b}_i \leq \bar{g}_{i,k} \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$

$(1-k) \sum \bar{b}_i \geq (1-k) \sum b_i$

$x_{l,i,k} = 0 \quad \forall l; \forall k$

$x_{l,m,k} + x_{m,l,k} = 1 \quad \forall l \neq m; \forall k$

$x_{l,n,k} \geq x_{l,m,k} + x_{m,n,k} - 1 \quad \forall l \neq m \neq n; \forall k$

$x_{l,n,k} + x_{m,n,k} = 1 \quad l \neq m \neq n$

$x_{l,m,k} = 1 \quad l \neq m$

$g_{i,k} = \beta_{i,l,k} \varphi_{i,k} \quad \forall i \in \Omega; \forall k \in \sigma_i$

$g_{i,k} = \beta_{i,l,k} \bar{\varphi}_{i,k} \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$

$0 \leq w_{i,k} + b_i \leq \sum \beta_{i,l,k} \varphi_{i,k} \quad \forall i \in \Omega; \forall k \in \sigma_i$

$0 \leq \bar{w}_{i,k} + \bar{b}_i \leq \sum \beta_{i,l,k} \bar{\varphi}_{i,k} \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$

---

Model III

$r_{i,k} = \sum \beta_{i,m,k} x_{i,m} \cdot \phi_{i,k} + M(1 - \beta_{i,m,k}) \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i; \forall m$

$r_{i,k} = \sum \beta_{i,m,k} x_{i,m} \cdot \phi_{i,k} + M(1 - \beta_{i,m,k}) \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i; \forall m$

$r_{i,k} + r_{i,k} + \sum \beta_{i,l,k} \cdot \phi_{k,n} = 1 \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i$

$b_i \leq y_i$

$\tilde{b}_i \leq \tilde{y}_i$

$\theta_k + r_{i,k} + w_{i,k} + t_k + n_{i,k} \geq \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + \tau_{i,k+1} + n_{i,k+1} - M(1 - y_{i}) \quad \forall i \in \Omega; \forall k \in \sigma_i$

$\theta_k + r_{i,k} + w_{i,k} + t_k + n_{i,k} \geq \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + \tau_{i,k+1} + n_{i,k+1} + M(1 - y_{i}) \quad \forall i \in \Omega; \forall k \in \sigma_i$

$\bar{\theta}_k + \bar{r}_{i,k} + \bar{w}_{i,k} - \bar{\tau}_{i,k} + \bar{t}_k + \bar{n}_{i,k} \geq -\theta_{k+1} + \bar{r}_{i,k+1} + \bar{w}_{i,k+1} + \bar{n}_{i,k+1} - M(1 - \bar{y}_{i}) \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$

$\bar{\theta}_k + \bar{r}_{i,k} + \bar{w}_{i,k} - \bar{\tau}_{i,k} + \bar{t}_k + \bar{n}_{i,k} \leq \bar{\theta}_{k+1} + \bar{r}_{i,k+1} + \bar{w}_{i,k+1} + \bar{n}_{i,k+1} + M(1 - \bar{y}_{i}) \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$

$\theta_k + r_{i,k} + w_{i,k} + t_k + n_{i,k} = \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + \tau_{i,k+1} + n_{i,k+1} + M(1 - y_{i}) \quad \forall i \in \Omega; \forall k \in \sigma_i$

$\bar{\theta}_k + \bar{r}_{i,k} + \bar{w}_{i,k} - \bar{\tau}_{i,k} + \bar{t}_k + \bar{n}_{i,k} \leq \bar{\theta}_{k+1} + \bar{r}_{i,k+1} + \bar{w}_{i,k+1} + \bar{n}_{i,k+1} - M(1 - \bar{y}_{i}) \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$
Numerical Test

Guangming 6th Rd W

Xianzhen 2nd Rd

Path 1
Path 2
Path 3
Path 4
Path 5
Three models are compared:

- Model 1: TRANSYT-7F optimization Model;
- Model 2: Proposed signal optimization model with MAXBAND for progression design;
- Model 3: Proposed model;

<table>
<thead>
<tr>
<th>Model</th>
<th>Intersection</th>
<th>CL</th>
<th>Φ1</th>
<th>Φ2</th>
<th>Φ3</th>
<th>Φ4</th>
<th>offset</th>
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<tbody>
<tr>
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<td>91</td>
<td>69</td>
<td>/</td>
<td>/</td>
<td>152</td>
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<td>160</td>
<td>41</td>
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<td></td>
<td>3</td>
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<td>75</td>
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<td>115</td>
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<td>108</td>
<td>47</td>
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<td>/</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>155</td>
<td>39</td>
<td>27</td>
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<td>95</td>
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<td>32</td>
<td>28</td>
<td>/</td>
<td>138</td>
</tr>
</tbody>
</table>
Numerical Test

- To evaluate the signal plans produced by different models, a simulation network is developed with VISSIM.

- Also, the VISSIM network has been well-calibrated with field data.

### Percentage difference between simulated and field volume data

<table>
<thead>
<tr>
<th>Intersection No.</th>
<th>Approach</th>
<th>WB</th>
<th>NB</th>
<th>EB</th>
<th>SB</th>
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<tr>
<td>1</td>
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<td>1%</td>
<td>0.6%</td>
<td>2%</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.9%</td>
<td>N/A</td>
<td>2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2%</td>
<td>3%</td>
<td>0.6%</td>
<td>1%</td>
</tr>
</tbody>
</table>

### Network performance under the control of different models

<table>
<thead>
<tr>
<th>MOEs</th>
<th>Model 1 TRANSYT 7-F</th>
<th>Model 2 MAXBAND</th>
<th>Model 3 Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Delay</td>
<td>54.3 secs</td>
<td>55.4 secs</td>
<td>47.6 secs</td>
</tr>
<tr>
<td>Average # of Stops</td>
<td>0.972</td>
<td>1.047</td>
<td>0.884</td>
</tr>
<tr>
<td>Average Speed</td>
<td>34.7 km/h</td>
<td>31.3 km/h</td>
<td>40.5 km/h</td>
</tr>
</tbody>
</table>

Department of Civil & Environmental Engineering
University of Maryland
The time-dependent travel time on freeway mainline

Numerical Test
Real-Time Signal Control

1. Traffic Detectors
   - OD Estimation Model
     - OD flow pattern
     - Critical Traffic Paths
   - Signal Optimization Model
     - Multi-path Progression Model
     - Pre-timed Signal Plan
2. Historical Traffic Data
3. Real-time signal Control
Real-Time Signal Control

Traffic Detection System

Off-ramp Queue Estimation

Potential Freeway Breakdown?

No
Arterial Adaptive Signal Control

Yes
Dynamic Off-ramp Priority Control
Location of dual-zone detectors on the target off-ramp

Short Detection Zone: collect traffic flow information;
Long Detection Zone: identify the presence of queue
This study proposed two models in response to different congestion levels at the off-ramp:

- Model I: off-ramp queue **can** be cleared during the green phase;
- Model II: off-ramp queue **cannot** be cleared during the green phase.
Model I

At time $\varepsilon$: 
$$\delta(\varepsilon, k) = \sum_{t=\varepsilon-t_{off}}^{\varepsilon} q_{up}(t, k)$$ 
equals the number of vehicles passed the upstream detector during time period $[\varepsilon - t_{off}, \varepsilon]$

At time $g_{off}$: 
$$\delta(g_{off}, k) = \delta(\varepsilon, k) + \sum_{t=g_{off}}^{g_{off}} q_{up}(t, k) - \sum_{t=\varepsilon}^{g_{off}} q_{down}(t, k)$$ 
plus # of arrivals and minus # of departures

At time $c$: 
$$\delta(c, k) = \delta(g_{off}, k) + \sum_{t=g_{off}}^{c(k)} q_{up}(t, k)$$ 
plus # of arrivals
Two additional scenarios might be encountered:

- Scenario 1: residual queue cannot reach the downstream detector;

- Scenario 2: residual queue can reach the downstream detector;
Scenario 1

At time $c$:

$$
\delta(c, k) = \sum_{t=\eta-t_{off}}^{c(k)} q_{up}(t, k)
$$

equals the number of vehicles passed the upstream detector during time period $[\eta - t_{off}, c]$
Scenario 2

If the residual queues have exceeded the downstream detector, the queue length at the end of a cycle can be approximated with:

\[
\tau_{off}(c, k) = \tau_{off}(c, k - 1) + \sum_{t=1}^{c(k)} q_{up}(t, k) - \sum_{t=1}^{c(k)} q_{down}(t, k)
\]

Last cycle queue  Total Arrivals  Total Departures
Real-Time Signal Control

Off-ramp Queue Estimation

Potential Freeway Breakdown?

No

Arterial Adaptive Signal Control

Yes

Dynamic Off-ramp Priority Control

Traffic Detection System
Arterial Adaptive Signal Control

Intersection Signal Timing Adjustment

**Objective**
Minimization of intersection Delays

**Solution Algorithm**
Gradient Search

Adaptive Signal Progression Design

**Objective**
Maximization of Progression Efficiency

**Solution Algorithm**
Dynamic Programming
Intersection Signal Timing Adjustment

**M1:**  Min  \( d_i(k) \)  

Minimization of intersection total delay

s.t.

\[
d_i(k) = \sum_{j=1}^{N_j} \sum_{t=1}^{C} r_{i,j}(t,k) \Delta t
\]

Total delay estimation with queue

\[
\mu_{i,j}(t,k) = \frac{1}{c} q_{i,j}(k) \quad \forall j, t
\]

Arrival rate calculation

\[
r_{i,j}(t,k) = \begin{cases} s_{i,j} \Delta t & \text{if green} \\ 0 & \text{if red} \end{cases} \quad \forall j, t
\]

Departure rate estimation

\[
r_{i,j}(0,k) = r_{i,j}(c,k-1) \quad \forall j
\]

Queue Estimation

\[
r_{i,j}(t,k) = \text{Max}[r_{i,j}(t-1,k) + \mu_{i,j}(t,k) - r_{i,j}(t,k), 0] \quad \forall j, t
\]

Common cycle length constraint

\[
\sum_{p=1}^{N_p} (g_{i,p}(k) + l_{i,p}(k)) = c(k)
\]

Min & Max green time constraint

\[
g_{i,p,\text{min}} \leq g_{i,p}(k) \leq g_{i,p,\text{max}}
\]

Max green time adjustment constraint
Solution Algorithm

Gradient Search Algorithm:

Step 1: Initialization. Let $p = 1$ and get the green time of each phase at the previous signal cycle.

Step 2: For phase $p$, change the green time by $\alpha$ seconds (could be negative or positive) by solving the following sub-problem:

$$
\alpha = \arg \min \{d_i(k); m \in N_p, m \neq p\}
$$

s.t. \quad g_{i,p}(k) = g_{i,p}(k-1) + \alpha

\quad g_{i,m}(k) = g_{i,m}(k-1) - \alpha

\quad -\Delta g_i \leq \alpha \leq \Delta g_i

\quad g_{i,p_{\min}} \leq g_{i,p}(k) \leq g_{i,p_{\max}}

\quad g_{i,m_{\min}} \leq g_{i,m}(k) \leq g_{i,m_{\max}}

Step 3: Let $p = p + 1$. If $p > |N_p|$, stop; otherwise go back to Step 2.
Adaptive Signal Progression Control

Green band of an outbound path between two intersections

Green band of an inbound path between two intersections
Adaptive Signal Progression Control

\[ M2: \max \sum_{i} \sum_{j} \phi_{i}(k) b_{i,j}(k) + \sum_{i} \sum_{j} \phi_{i}(k) \bar{b}_{i,j}(k) \]  
Maximization of total green bandwidths

s.t.

\[ b_{i,j}(k) = \max[\min(t_{j+1,i,j,2}(k), t_{i,j,1}(k) + t_{i,j,1}(k)) - \max(t_{i,j,1}(k) + t_{i,j,1}(k), t_{i,j,1}(k)), 0] \]  
Estimation of green bandwidth for an outbound path

\[ \bar{b}_{i,j}(k) = \max[\min(t_{i,j,2}(k), t_{i,j,2}(k) + t_{i+1,j}(k)) - \max(t_{i,j,1}(k), t_{i,j,1}(k) + t_{i+1,j}(k)), 0] \]  
Estimation of green bandwidth for an inbound path

\[ t_{i,j,1}(k) = \sum_{q} \sum_{p} \xi_{i,j,p} \varphi_{p,q} g_{i,p}(k) + \theta_{i}(k) \]  
Identification of start of green for path \( i \)

\[ t_{i,j,2}(k) = \sum_{q} \sum_{p} \xi_{i,j,p} \varphi_{p,q} g_{i,p}(k) + \sum_{p} \xi_{i,j,p} \varphi_{p,q} g_{i,p}(k) + \theta_{i}(k) \]  
Identification of end of green for path \( i \)

\[ \theta_{i}(k-1) - \Delta \theta_{i} \leq \theta_{i}(k) \leq \theta_{i}(k-1) + \Delta \theta_{i} \]  
Max allowed offset adjustment constraint
Solution Algorithm

Dynamic Programming:

Let $f(.)$ denote the accumulated performance measure, the algorithm consists of the following steps:

Step 1: set $i = 1$, $\theta_i(k) = 0$, and $f_i(0) = 0$;

$$\Theta_i(k) = \{\theta_i(k-1) - \Delta \theta_i, \theta_i(k-1) - \Delta \theta_i + 1, \ldots, \theta_i(k-1) + \Delta \theta_i\}$$

Step 2: $i = i + 1$;

$$f_i(\theta_i^*(k)) = \min_{\theta_i(k)} \left\{ f_{i-1}(\theta_{i-1}^*(k)) + B_i(\theta_i(k)) \mid \theta_i \in \Theta_i(k) \right\}$$

Record $\theta_i^*(k)$ as the optimal solution in Step 2.

Step 3: if $i < N_i$, go to Step 2.

Else, Stop.
Solution Algorithm

Dynamic Programming:

Intersection 1

Intersection 2 ... Intersection j ... Intersection n
Real-Time Signal Control

Off-ramp Queue Estimation

Potential Freeway Breakdown?

No

Arterial Adaptive Signal Control

Yes

Dynamic Off-ramp Priority Control

Traffic Detection System
Dynamic Off-ramp Priority Control

Intersection Signal Timing Adjustment

Objective
Minimization of intersection Delays

Solution Algorithm
gradient search

Adaptive Signal Progression Design

Objective
Maximization of Coordination Efficiency

Solution Algorithm
Dynamic programming
1) increasing the green time for the off-ramp flows;
2) providing signal progression priority to those path-flows from the target off-ramp.
Intersection Signal Timing Adjustment with Off-ramp Priority

Step 1: computation of the minimum green extension to off-ramp flows

\[
L_{off} - \tau_{off}(c, k-1) + \text{Max} [s_{off} g_{off}(k) - q_{off}(k), \sum_{m=k}^{k+1} (s_{off} g_{off}(m) - q_{off}(m))] \\

\frac{e_{off}^{\text{min}} (k)}{s_{off}}
\]

The minimal green extension will ensure the prevention of queue spillover until the end of the following signal cycle.
Intersection Signal Timing Adjustment with Off-ramp Priority

Step 2: adaptive signal control with off-ramp priority

\[ M3: \quad \text{Min} \quad d_i(k) \]

s.t.

\[ d_i(k) = \sum_{j=1}^{N_i} \sum_{t=1}^{c} \tau_{i,j}(t,k) \Delta t \]

\[ \mu_{i,j}(t,k) = \frac{1}{c} q_{i,j}(k) \quad \forall j, t \]

\[ r_{i,j}(t,k) = \begin{cases} s_{i,j} \Delta t & \text{if green} \\ 0 & \text{if red} \end{cases} \quad \forall j, t \]

\[ \tau_{i,j}(0,k) = \tau_{i,j}(c,k-1) \quad \forall j \]

\[ \tau_{i,j}(t,k) = \max[\tau_{i,j}(t-1,k) + \mu_{i,j}(t,k) - r_{i,j}(t,k), 0] \quad \forall j, t \]

\[ \sum_{p=1}^{N_j} (g_{i,p}(k) + l_{i,p}(k)) = c(k) \]

\[ g_{i,p_{\text{min}}} \leq g_{i,p}(k) \leq g_{i,p_{\text{max}}} \]

\[ g_{i,p}(k-1) - \Delta g_i \leq g_{i,p}(k) \leq g_{i,p}(k-1) + \Delta g_i \]

\[ g_{\text{off}}(k) - g_{\text{off}}(k-1) \geq e_{\text{off}}^{\text{min}}(k) \]

Green extension constraint
Adaptive Signal Progression Control with Off-ramp Priority

\[ M4: \quad Max \sum_i \sum_l \phi_l(k) b_{i,l}(k) + \sum_i \sum_l \phi_l(k) \bar{b}_{i,l}(k) \]

s.t.

\[ b_{i,1}(k) = Max[Min(t_{i+1,j,2}(k), t_{i,j,2}(k) + t_{i,i+1}(k)) - Max(t_{i,j,1}(k) + t_{i,i+1}(k), t_{i,j,1}(k)), 0] \]

\[ \bar{b}_{i,j}(k) = Max[Min(t_{i,j,2}(k), t_{i+1,j,2}(k) + t_{i+1,i}(k)) - Max(t_{i,j,1}(k), t_{i,j,1}(k) + t_{i+1,i}(k)), 0] \]

\[ t_{i,j,1}(k) = \sum_q \sum_p \zeta_{i,j,p} g_{i,p}(k) + \theta_j(k) \]

\[ t_{i,j,2}(k) = \sum_q \sum_p \zeta_{i,j,p} g_{i,p}(k) + \sum_p \zeta_{i,j,p} g_{i,p}(k) + \theta_j(k) \]

Min bandwidth constraint for off-ramp path-flows
Numerical Test
Queue Estimation Accuracy

Comparison of estimated and actual queue length at the off-ramp

The estimation errors of the off-ramp queue estimation model
Numerical Test

Activation of off-ramp priority control function

Green extension time granted to the off-ramp flows
System Evaluation

The following three systems are tested for comparison:

- Pre-timed Control System: using the proposed pre-timed models to generate the signal plans;

- Adaptive Control System: only the proposed adaptive signal control model and dynamic signal progression model are implemented;

- Proposed System: including the off-ramp queue estimation, arterial signal adaptive control, and off-ramp priority control.
The time-dependent travel time along the freeway mainline
## Numerical Test

### Network Performance

<table>
<thead>
<tr>
<th>Performance Index</th>
<th>Pre-timed System</th>
<th>Adaptive System</th>
<th>Proposed System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave number of stops</td>
<td>2.391</td>
<td>1.711 (-28.4%)</td>
<td>1.621 (-32.2%)</td>
</tr>
<tr>
<td>Ave speed (km/h)</td>
<td>36.116</td>
<td>38.633 (+7.0%)</td>
<td>39.25 (+8.7%)</td>
</tr>
<tr>
<td>Ave Network delay (s)</td>
<td>89.065</td>
<td>73.77 (-13.7%)</td>
<td>68.209 (-19.6%)</td>
</tr>
</tbody>
</table>
Outline

1. Research Background & Literature Review
2. Primary Tasks & Modeling Framework
3. System Framework & Model Formulations
4. Conclusions and Future Research Directions
Summary of Contributions:

- Developed an effective operational framework for the integrated traffic control at the off-ramp interchanged area;

- Constructed a new O-D estimation model with real-time queue information;

- Formulated a signal optimization model to prevent the off-ramp queue spillover;

- Proposed a multi-path progression model to facilitate traffic flows to reach their destinations;

- Advanced all key control models for real-time operations, in response to traffic fluctuations in practice.
Conclusions

Future Research Directions:

- Development of an optimal traffic control model to concurrently account for the delay of traffic flows on the freeway and local arterial;

- Integration of both on-ramp and off-ramp control strategies (ramp metering, variable speed limit, off-ramp priority, local signal adaptive control) for a large-scale corridor traffic management;

- Enhancement of the current real-time signal control system with advanced information/communication technologies (e.g., connected vehicles).
THANKS & Questions?